PDL Measurements using the Agilent 8169A Polarization Controller

Product Note

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Introduction

This paper discusses methods of polarization dependent loss (PDL) measurements, particularly PDL measurements using a waveplate-type polarization controller and Mueller-Stokes analysis.

The discussion includes the mathematical derivation and the achievable accuracy. An extension of this technique for the characterization of integrated optics components is also mentioned.

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Using this method requires a calibration of the polarization controller for all used states of polarization, because the polarization controller usually produces polarization dependent power changes (internal PDL). During PDL measurement, the same calibrated polarization states have to be set again. This is very time consuming. The time for measuring one PDL value is in the order of 30 seconds or more, except if selected components are used for the measurement setup.

If the PDL of the polarization controller is small in comparison with the desired measurement accuracy, then no calibration is necessary and the polarization can be varied randomly. A measurement time of 2 seconds can be achieved in combination with a fast optical power meter (average time = 20 ms) and taking 100 measurement points. This is the principle of the E5574A optical loss analyzer.

The second PDL measurement principle is to apply well known polarization states to the device under test (DUT). In this case, the polarization dependent loss is measured with an optical power meter at four different, well known polarization states. The Mueller / Stokes analysis is then used to calculate the PDL. An advantage of this method is that arbitrary polarization states can be synthesized this way.

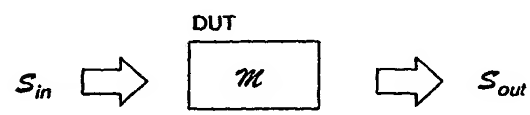
In the following section, the Mueller / Stokes method for determining PDL and its practical realization using an 8169A polarization controller are described.

2. Theory of the PDL Measurement using Mueller / Stokes Analysis

The Stokes vector $\mathcal{S} = (S0, S1, S2, S3)$ completely describes the power and polarization state of an optical wave. Each element of the vector is based on measured power levels. $S0$ is the total intensity. $S1$ describes the amount of linear horizontal ($S1 > 0$) or vertical polarization ($S1 < 0$). $S2$ describes the amount of linear +45° ($S2 > 0$) or -45° ($S2 < 0$) polarization, and $S3$ describes the amount of right-hand ($S3 > 0$) or left-hand circular ($S3 < 0$) polarization. For completely polarized light, the following relationship between the Stokes vector elements applies:

$$S0^2 = S1^2 + S2^2 + S3^2 \tag{1}$$

An incident polarized wave, characterized by the Stokes vector, $\mathcal{S}_{in}$, interacts with the optical component (DUT). The emerging lightwave can be characterized again as a Stokes vector. The interaction of the polarized light with the optical component can be described with the Mueller matrix, $\mathcal{M}$, a 4 x 4 real matrix. So the following matrix equation can be written:



$$\mathcal{S}_{out} = \mathcal{M} \bullet \mathcal{S}_{in} \tag{2}$$

This matrix equation represents four linear equations, but only the first is interesting for PDL calculation, because $S0_{out}$ represents the total output power. The equation derived from the first row of the Mueller matrix is as follows (the m_{1k} elements with $k = 1, 2, 3, 4$ represent the first row of the Mueller matrix):

$$S0_{out} = m_{11}\, S0_{in} + m_{12}\, S1_{in} + m_{13}\, S2_{in} + m_{14}\, S3_{in} \tag{3}$$

The first task is to determine the m_{1k} elements. To accomplish this, four different well defined states of polarization, $\mathcal{S}_{in} = (S0, S1, S2, S3)$, are applied to the device under test. These states contain essentially the same optical power: a slight power variation is only introduced by the internal PDL of the polarization controller.

3. PDL Measurement with the 8169A Polarization Controller

To obtain highly accurate PDL values, e.g. to the order of ±0.001 dB, it is necessary to do the following:

a) Calibrate the test setup for the four polarization states as described above to determine the insertion loss changes of the polarization controller versus polarization;
b) Use a very stable laser source or monitor the optical power fluctuations of the source by using a fiber optic coupler;
c) Use a detector with lowest PDL.

A PDL test setup using a stable laser source is shown in Fig. 2. The 8169A polarization controller is used to generate the necessary polarization states, with the help of the instrument's quarter-wave (Q) and half-wave (H) retardation plates. An optical isolator ensure stable output power. Only one optical head is necessary for this type of measurement, in this case an InGaAs type optical head with depolarizing filter.

The accuracy of this setup may be further improved by adding a coupler and a monitor power meter at the output of the polarization controller. By measuring ***power ratios*** instead of just powers, any changes in optical power can be cancelled out. The second power meter may have higher polarization dependence without affecting the measurement result. The polarization dependence of the coupler has no influence either. However, the monitoring option is not further discussed here.

4. PDL Measurement Process

Before the calibration, the polarizer (P) at the input of the polarization controller should be adjusted to maximize the output power of the polarization controller, because otherwise a large loss may occur at the polarizer. From here on, this offset angle is called α_P. The angles of the quarter-wave plate (Q) and the half-wave plate (H) must be set with respect to α_P.

During calibration four different polarization states are generated by the polarization controller, as described above. Table 2 shows the settings of the polarizer, of the quarter-wave plate and of the half-wave plate (values in degree). These settings are most precise for the wavelength 1540 nm. At this wavelength, the retarders exhibit their nominal quarter-wave respectively half-wave retardation.

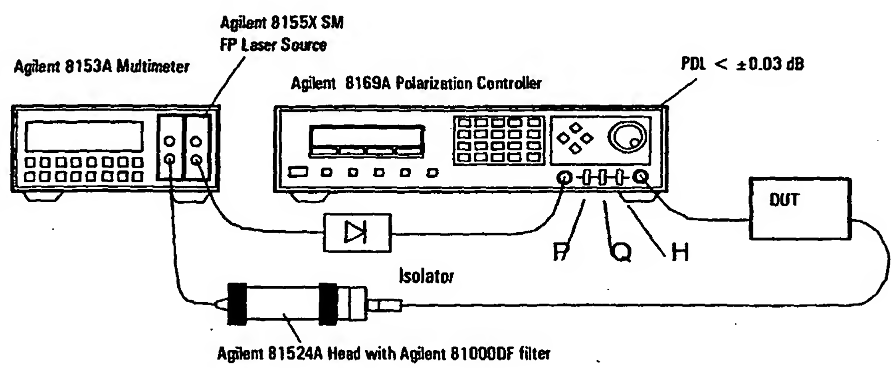


Figure 2: PDL test setup based on stable laser source

	Linear vertical		Linear diagonal		RH circular	
λ (nm)	Q-Plate	H-Plate	Q-Plate	H-Plate	Q-Plate	H-Plate
1580	2.5°	46.2°	1.7°	23.3°	42.9°	-17.1°
1560	1.2°	45.6°	0.8°	22.9°	44°	-16.5°
1540	0°	45°	0°	22.5°	45°	-15.1°
1520	-1.4°	44.3°	-1°	22°	46.2°	-13.8°
1500	-2.7°	43.6°	-2°	21.4°	47.4°	-12.4°
1340	-14.7°	36.2°	-13.9°	12.8°	58.1°	-0.7°
1320	-16.3°	35.1°	-16°	11°	59.6°	1°
1300	-17.9°	34°	-18.5°	8.9°	61.2°	3°
1280	-19.6°	32.9°	-21.2°	6.5°	62.9°	5.1°
1260	-21.2°	31.7°	-24.2°	3.9°	64.7°	7.4°

Table 4: Numerical values of the waveplate positions for selected wavelengths.
For wavelength values between listed values a linear approximation is suggested.

If the of the PDL accuracy requirement approaches ±0.001 dB, and the wavelength is outside the 1520 - 1560 nm band, then the wavelength dependent retardations have to be corrected, i.e. wavelength dependent waveplate settings have to be used.

Table 4 shows the wavelength dependent positions for retarders of the zero order type for linear vertical (90°), linear diagonal (+45°) and circular (RH) polarized light. For horizontally polarized light the same positions as before can be used, because the fast axis of the retarders is parallel to the polarization axis of the polarizer. This is wavelength independent.

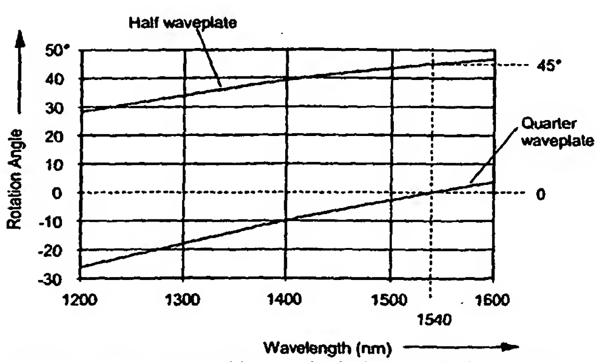


Figure 3: Waveplate positions to obtain linear vertical polarization state

Figures 3 to 5 show the wavelength dependencies of the waveplate positions in graphical form. Interpolation can be used to extend the wavelength beyond 1600 nm.

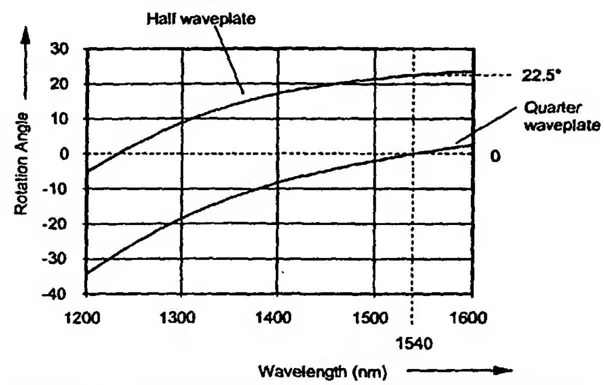


Figure 4: Waveplate positions to obtain linear diagonal polarization state

polarization state. Therefore, the detector's PDL has no influence on the measured PDL value.

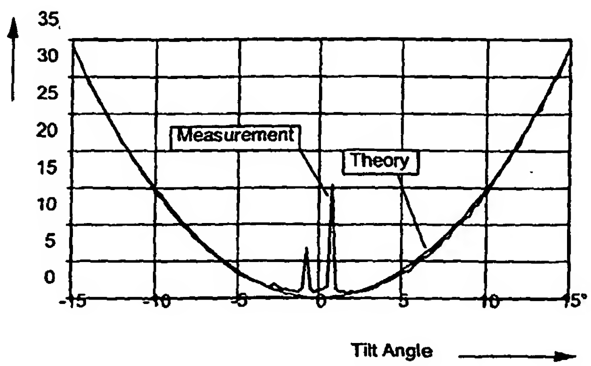


Figure 6: PDL measurement of tilted glass plate

Experimental and theoretical PDL values coincide within 0.001 dB, except in the region between -2° and +2°. Multiple reflections between the DUT and the fiber connector occur in this angle range. This causes non-predictable uncertainties in the measurement result (see figure 6). The almost perfect agreement between experimental and theoretical data demonstrates how well this measurement method works. The repeatability for the described measurement set was around 0.001 dB.

The time for this PDL measurement depends on the settling time of the polarization controller and the average time of the optical power meter. Both can be very fast. The typical settling time for the 8169A polarization controller is less than 200 ms and the average time of the 8163A optical power meter can be set to 50 ms. So it will take less than 4 x (200 ms + 50 ms) = 1 s to obtain one PDL measurement value.
This method was described by Nyman [1] at the Optical Fiber Conference 1994. Nyman reported the same accuracy and repeatability of 0.001 dB for the PDL measurement.

6. Testing integrated optics devices

A frequent question in context with testing integrated optics devices is: how can the desired horizontal and vertical polarization states (at the device input) be generated? The problem is that the state of polarization at the output of a standard single-mode fiber is completely unpredictable.

One possibility is using polarization maintaining fiber and mechanical rotators. However, the necessary rotation precision is very difficult to achieve; quite often, a lateral offset is obtained during the rotation. The other possibility, using a polarization controller and conventional single mode fiber, is usually not applicable because the polarization state at the end of the fiber is unknown. Does an intelligent solution, with electronic control, exist ?

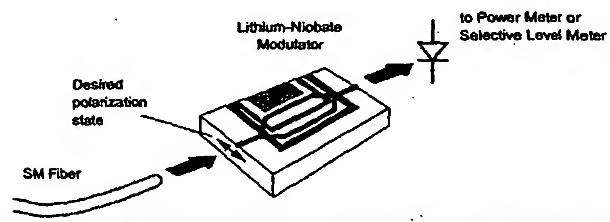


Figure 7: Generating horizontal or vertical polarization states to test integrated optical devices

Such a possibility is based on the assumption that the test device has sufficient PDL, and that the max / min transmissions occur at the horizontal / vertical (linear) polarization states. In this case, the Mueller method (originally a PDL test method) can be used to set the desired polarization states.

In many cases, a better criterion for the control of the polarization state is the modulation transfer function, e.g. at a fixed frequency of 10 MHz. In lithium-niobate modulators, for example, the insertion loss is only a weak function of the input polarization state. In contrast, the ***modulation depth*** is strongly dependent on the polarization. For such devices, the power meter should be replaced by a combination of (polarization-insensitive) photodetector and selective level meter or electrical spectrum analyzer.

The benefit from using the Mueller method is that the polarization states (Stokes vectors) leading to min / max

7. Summary

This paper describes how to measure PDL of optical components. It was shown that the Mueller matrix method allows fast and accurate PDL measurements. In addition, the Mueller method can be used to generate well defined polarization states for the test of integrated optical devices. To perform a PDL measurement with this method a highly precise and repeatable polarization controller such as the 8169A is mandatory. It was shown that this instrument can not only be used at its design wavelength around 1540 nm, but also around 1300 nm using wavelength dependent retarder settings.

Literature

[1] Nyman, B., Optical Fiber Conference, OFC 1994, Technical Digest, page 230, ThK6

[2] Bronstein, I. N., Semendjajew, K. A. (1987) Taschenbuch der Mathematik,
23rd edition, page 287. Leipzig : Teubner Verlagsgesellschaft

[3] E. Collet, "Polarized light, fundamentals and applications", Marcel Dekker Inc., New York 1993, ISBN 0-8247-8729-3

Appendix: Mathematical derivation

When totally polarized light can be assumed, then the transfer of polarized light through a test component (DUT) can be described as shown in figure 10:

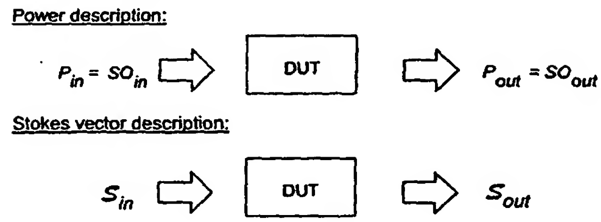


Figure 10: Two possible descriptions of the power transfer through an optical component

The input power is SO_{in} . The output power, SO_{out} , can be calculated from the first row of the Mueller matrix of the DUT:

$$SO_{out} = m_{11}\, SO_{in} + m_{12}\, S1_{in} + m_{13}\, S2_{in} + m_{14}\, S3_{in}$$

For totally polarized light, the Stokes vector components are related by:

$$SO_{in}^{\ 2} = S1_{in}^{\ 2} + S2_{in}^{\ 2} + S3_{in}^{\ 2} \qquad \text{(A2)}$$

or: $$\left(\frac{S1_{in}}{SO_{in}}\right)^2 + \left(\frac{S2_{in}}{SO_{in}}\right)^2 + \left(\frac{S3_{in}}{SO_{in}}\right)^2 = 1 \qquad \text{(A3)}$$

The power transmission is defined as:

$$T = \frac{SO_{out}}{SO_{in}} \qquad \text{(A4)}$$

$$T = \frac{m_{11}\, SO_{in} + m_{12}\, S1_{in} + m_{13}\, S2_{in} + m_{14}\, S3_{in}}{SO_{in}} \qquad \text{(A5)}$$

$$T = m_{11} + m_{12}\frac{S1_{in}}{SO_{in}} + m_{13}\frac{S2_{in}}{SO_{in}} + m_{14}\frac{S2_{in}}{SO_{in}} \qquad \text{(A6)}$$

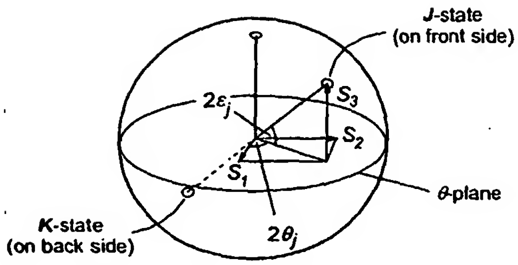


Figure 11: Constructing the desired polarization states

The result is the following: to obtain the J-state, the waveplates must be rotated by the following mechanical angles (starting at 0°), to be calculated from the known Stokes elements S_1 to S_3. The last part of equation A24 represents the correction for the undesired θ_{offset} caused by the Q-plate:

$$\alpha_Q = \frac{\arcsin(S_3)}{2} \qquad \text{(A23)}$$

$$\alpha_H = \frac{\theta_j}{2} + \frac{\arcsin(S_3)}{4} \qquad \text{(A24)}$$

where $2\theta_j$ is the angle obtained from rectangular-to-polar conversion of S_1 and S_2 (the additional angle of 180° is applicable when the Stokes elements S_1 and S_2 form an angle $2\theta_j$ outside of the -90° to +90° range):

$$2\theta_j = \arctan\left(\frac{S_2}{S_1}\right) + \begin{matrix} 0^\circ \\ 180^\circ \end{matrix} \qquad \text{(A25)}$$

To obtain the K-state, all S-values must be replaced by minus S. The angle $2\theta_k$ can be calculated by adding 180° to $2\theta_j$ because the J- and K-states are on opposite sides of the Poincaré sphere.

Finally, we must take into account that the input polarizer was rotated to maximize the power. This means a simple correction: we assume that the polarizer was mechanically rotated by an angle α_P. Then α_P must be added to both α_Q and α_H in the equations above.